



LA-UR -81-1232
CONF-810429-11

TITLE: Small-Signal-Gain Spectrum of an 1800-Torr CO₂ Amplifier

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SUBMITTED TO: Proceedings of the Los Alamos Conference on Optics '81

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Small-Signal-Gain Spectrum of an 1800 Torr CO₂ Amplifier*

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Abstract

Prominent hot-band effects have been observed in the 9.4 and 10.6 μm gain spectrum of an 1800 Torr electron-beam-controlled-discharge CO₂ laser amplifier. The data are in good agreement with theoretical calculations at 53 different frequencies.

Introduction

Suppression of parasitic oscillations is essential for the operation of high-energy, high-gain, short-pulse amplifiers in ICF laser systems. It is necessary to accurately know a CO₂ amplifier's gain spectrum over both the 9.4 and 10.6 μm bands in order to prepare an optimum mixture of absorber gases which reduces below the parasitic threshold the net small-signal gain at all frequencies, but simultaneously allows maximum transmission of the amplified short pulse. This paper reports measurements of the small-signal gain coefficients of 53 different lines in the P and R branches of the 9.4 and 10.6 μm bands of an 1800 Torr electron-beam-controlled-discharge CO₂ amplifier. It is also demonstrated that the data, which constitute the most complete set of gain vs line frequency measurements for this type of CO₂ laser yet published, are in good agreement with a theoretical calculation which used as input only measured electrical characteristics and no other variable parameters. An important feature of the calculation is the inclusion of hot-band and line-overlap effects² which can make 10-20% changes in the basic two-level gain coefficients of many lines. The agreement between the theory and measurements confirms the validity of the theoretical model which can now be confidently applied under other pumping conditions.

Experiment

In the present experiment two 20 Torr CO₂ lasers with chopped CW output beams were used to measure the gain along the centerline optical axis of one of the eight amplifiers of the HELIOS laser system.³ The clear aperture of the amplifier is 35 cm while the pumped gain length is 200 cm. For this experiment the amplifier was operated with 1800 Torr of a 3/0.25/1 gas mixture of He/N₂/CO₂. A schematic of the experimental arrangement is shown in Fig. 1. The frequency of one of the low pressure lasers was held constant (usually on the 10.6 μm P22 line) to monitor shot-to-shot fluctuations in the amplifier gain (typically 2-3%). The frequency of the other laser was tuned to different lines throughout the 9.4 and 10.6 μm

Work performed under the auspices of the U.S. Department of Energy.

bands. In Fig. 2 the experimental procedure is further illustrated: each chopper wheel had four apertures, two clear and two covered by a known thickness of attenuator material (CaF_2 or mylar). This resulted in a sequence of pulses, alternately unattenuated and attenuated. The timing of the amplifier pump pulse (which lasted several microseconds) was arranged to occur near the center of the attenuated probe pulse which had a duration of several milliseconds. The chopper wheel attenuation was selected so that the gain of the amplifier would produce a peak intensity for the amplified pulse comparable to that of an unattenuated pulse which passed through the unpumped amplifier. By comparing the height of the amplified signal to that of the unattenuated signal (reduced by the cold CO_2 absorption), the maximum small-signal gain could be extracted from the data. The time history of the gain was measured on each shot, but only the peak small-signal gain coefficients for 53 different transitions are shown in Figs. 3 and 4 for the 9.4 and 10.6 μm bands respectively. The statistical (relative) errors in the data are about the size of the open circles plotted in the figures (3%); the scale errors in the gain coefficients are thought to be of the order of 5%.

Theory and Discussion

The theoretical points shown in Figs. 3 and 4 were obtained from a spectrum synthesis program⁴ that used as input data, CO_2 vibrational temperatures calculated from a discharge kinetics code.^{5,6} The kinetics code, using only currents and voltages derived from measurements and no adjustable parameters, computed the excitation temperatures from a theory that assumes a spatially homogeneous discharge to obtain approximate pumping conditions at the center of the laser amplifier. A schematic of the energy flow in the kinetic model used in the discharge code is shown in Fig. 5. Electrons in the discharge collide inelastically with N_2 and CO_2 and pump the vibrational modes of these molecules with various rate constants k_i . The relationship of some of the lower-lying CO_2 and N_2 energy levels are shown in Fig. 6. The kinetics model assumes that the excitation of the vibrational levels of CO_2 can be described in terms of time-dependent temperatures for each of the three vibrational modes. Due to strong couplings like that indicated in Fig. 6 between the 10^00 and 02^00 levels, it is further assumed that the temperatures of the symmetric stretch (S) and bending (B) modes are always equal. The asymmetric stretch (A) mode, which includes the upper laser level 00^01 , is pumped by electron collisions from the ground state with rate constant k_A and by collisional transfer from vibrationally excited N_2 with rate constant τ_{VV} . A complete exposition of the kinetics code, including its treatment of many important processes that have not been specifically mentioned here, can be found in Ref. 6. The amplifier parameters appropriate to the present experiment, which were used to derive input data for the kinetics code, are shown in Table 1.

The kinetics code yielded the CO_2 mode temperatures as a function of time after initiation of the discharge. The time to maximum gain for the 10.6 μm P20 line was calculated to be 3.5 μs , in agreement ($\pm 0.1 \mu\text{s}$) with the measured value. The mode temperatures, and the translational gas temperature (which equals the rotational temperature) at the time of peak P20 gain were found to be: $T_{3B} = 390.0^\circ\text{K}$, $T_A = 1381.7^\circ\text{K}$, and $T_{\text{gas}} = 364.8^\circ\text{K}$. These temperatures were then used as input data to a spectrum synthesis code⁴ which computed values for the gain coefficients of

all of the 9.4 and 10.6 μm transitions shown in Figs. 3 and 4. The spectrum synthesis code includes the effects of eight different hot- and sequence-bands (which have transitions that accidentally lie close in frequency to some of the main 9.4 and 10.6 μm lines) in addition to the basic nine and ten micron bands; it also includes line-overlap contributions due to the finite linewidth of each transition.

The results of the spectrum synthesis code are shown as solid triangles in Figs. 3 and 4, while the effects of deleting hot- and sequence-bands and line-overlap contributions from the calculation are shown by the solid lines. One notes that the calculated points are in generally good agreement with the measurements, and that excited-state and line-overlap contributions are significant for most of the observed lines. These results have been obtained using only measured electrical characteristics of the amplifier and known spectroscopic properties of CO_2 -- no fitting or variation of parameters of any kind was done.

Using mode temperatures from the kinetics code near the time of peak P20 gain, the spectrum synthesis code showed that the peak gain coefficients for low angular momentum quantum number J lines actually occurred 0.1-0.2 μs earlier than the time of peak P20 gain, while the high J lines reached maximum gain 0.1-0.2 μs after the P20. Although this type of temporal behavior is qualitatively consistent with the data, a quantitative statistical comparison with the experimental data was not done. The effect is due to a slow increase of the gas temperature with time. For most lines, the difference between the peak value and the gain at the time of maximum P20 gain was very small, although this is a source of small errors in comparing the data with the theory which computes the gain of all lines at the time of peak P20 gain.

Summary

The small-signal gain coefficients of 53 different lines in the P and R branches of the 9.4 and 10.6 μm bands of CO_2 have laser been measured in an 1800 Torr electron-beam-controlled-discharge laser amplifier. Prominent hot- and sequence-band contributions, and line overlap effects, have been observed on many lines. Using only measured discharge parameters, the Los Alamos CO_2 kinetics code⁶ and spectrum synthesis code⁴ have computed peak small-signal gain coefficients along the amplifier's centerline optical axis to better than 10% for most lines. This level of agreement is highly significant in view of the fact that no fitting of any sort was carried out, and also because there exist numerous possible sources of small (~1%) errors which broaden the possible range of gain values (e.g., correction for the unpumped CO_2 absorption coefficients, possible pressure shifts between the 20 Torr probe lasers and the 1800 Torr amplifier, the peaking of gain for different lines at different times, etc.). Although a few transitions show large deviations from the theoretical predictions (which may be due to other excited-state effects not yet included in the spectrum synthesis code), our results confirm the validity of the basic theoretical model which can be reliably used to predict gain coefficients under other pumping conditions.

Table 1.

Amplifier Parameters

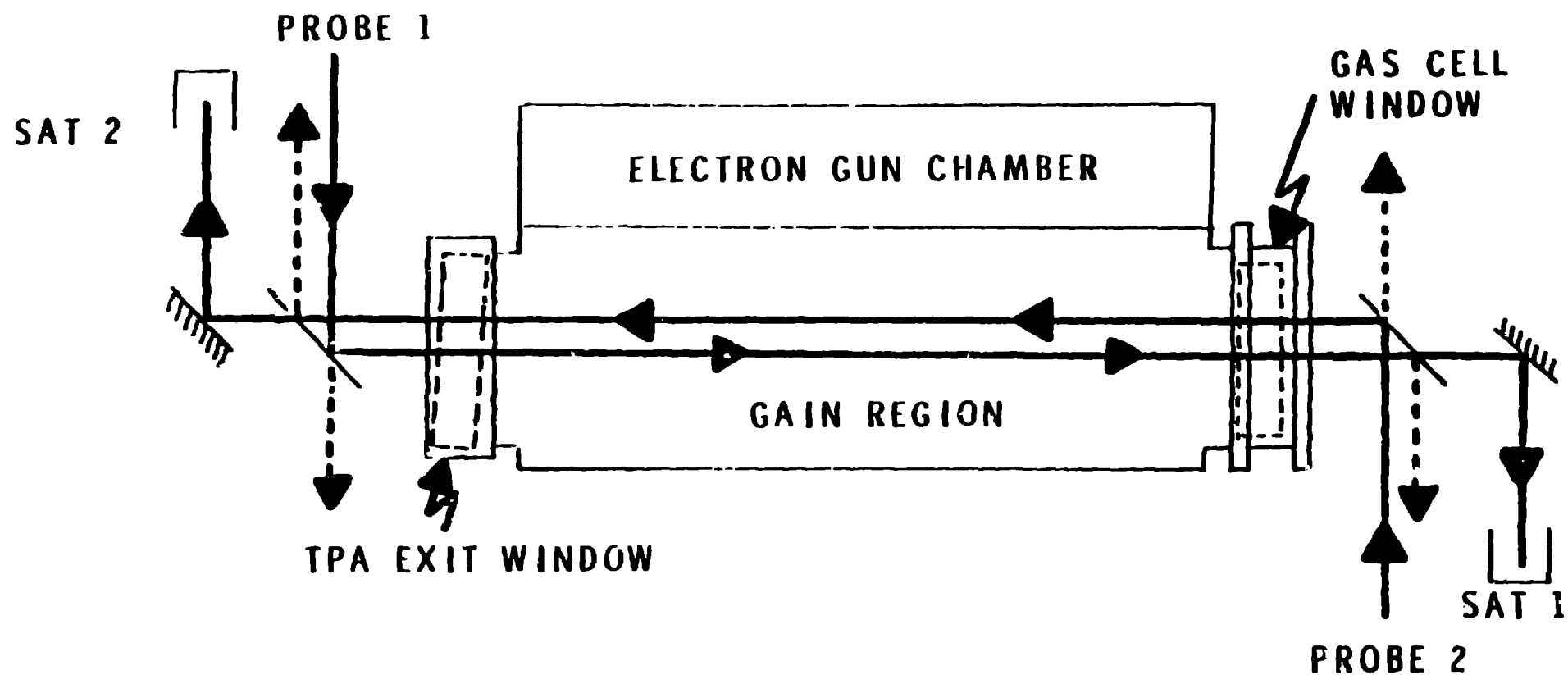
3/0.25/1 mixture of He/N₂/CO₂ at 1800 Torr
electron beam 55 KV per stage
sustainer PFN 52 KV per stage
peak discharge voltage 225 KV
peak discharge current 844 KA
electrode dimensions: width 34 cm
 height 35 cm
 length 200 cm
peak electric field 6.62 KV/cm
peak current density 12.06 A/cm²
energy stored in capacitor bank 65.8 kJ
time to peak voltage 2.5 μ sec

References

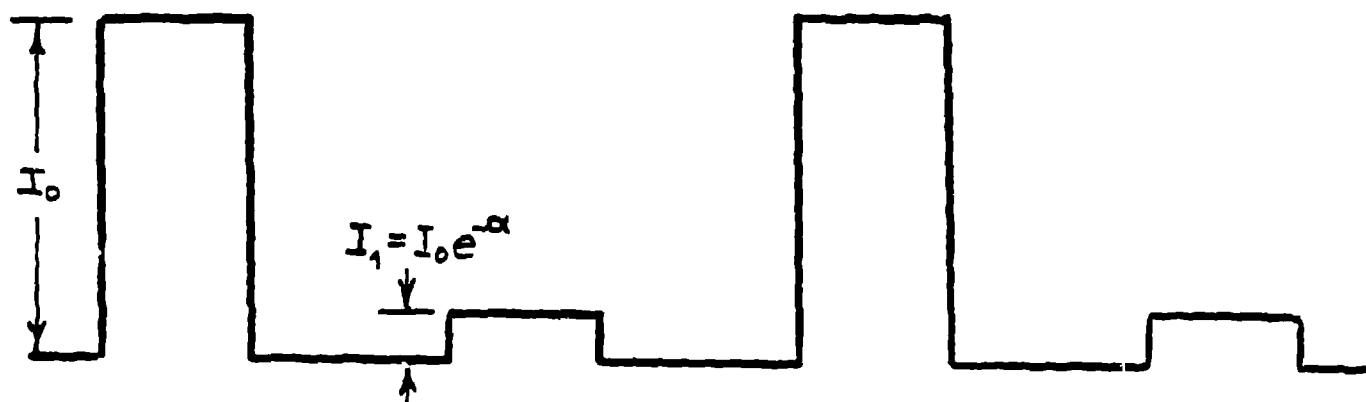
1. R. F. Haglund, Jr., D. E. Casperson, S. J. Czuchlewski, C. J. Elliott, J. C. Goldstein, J. S. Ladish, and A. V. Nowak, "Proceedings of the Los Alamos Conference on Optics '79," D. H. Liebenberg ed., SPIE 190, 178 (1979).
2. J. Reid and K. J. Siemsen, IEEE J. Quant. Electron. 14, 217 (1977). Roderick S. Taylor, A. J. Alcock, Walter J. Sargeant, and Kurt E. Leopold, IEEE J. Quant. Electron. 15, 1131 (1979).
3. G. T. Schappert, in "Electro-Optics/Laser '79 Conference and Exposition," Anaheim, CA, (Industrial and Scientific Conference Management, Inc., Chicago, IL, 1979), 457.
4. J. C. Goldstein, "Proceedings of the Los Alamos Conference on Optics '79," D. H. Liebenberg ed., SPIE 190, 327 (1979).
5. A. M. Lockett, III, Twenty-Sixth Annual Gaseous Electronics Conference, Madison, WI, 1973.
6. J. C. Comly, Jr., W. T. Leland, C. J. Elliott, A. M. Hunter, II, and M. J. Kircher, "Discharge and Kinetics Modeling in Electron-Beam-Controlled CO₂ Laser Amplifiers," IEEE J. Quant. Electron., to be published.

Figure Captions

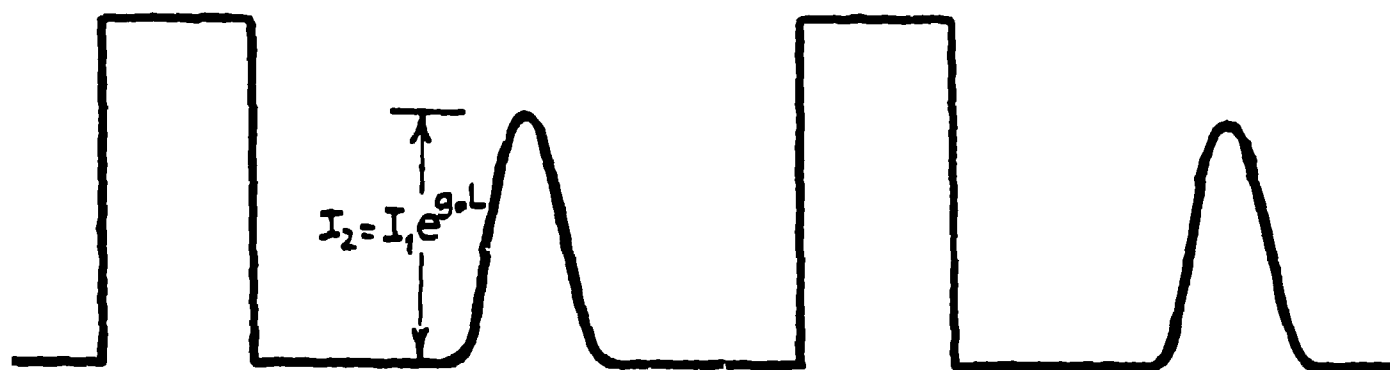
- Figure 1: Experimental layout for small-signal gain measurements.
- Figure 2: Chopped cw beams and measurement technique.
- Figure 3: Measured and calculated gain coefficients for the 9.4 μm band.
- Figure 4: Measured and calculated gain coefficients for the 10.6 μm band.
- Figure 5: Energy flow among thermal reservoirs in He/N₂/CO₂ laser kinetics.
- Figure 6: Energy levels and modes in the He/N₂/CO₂ kinetics model.



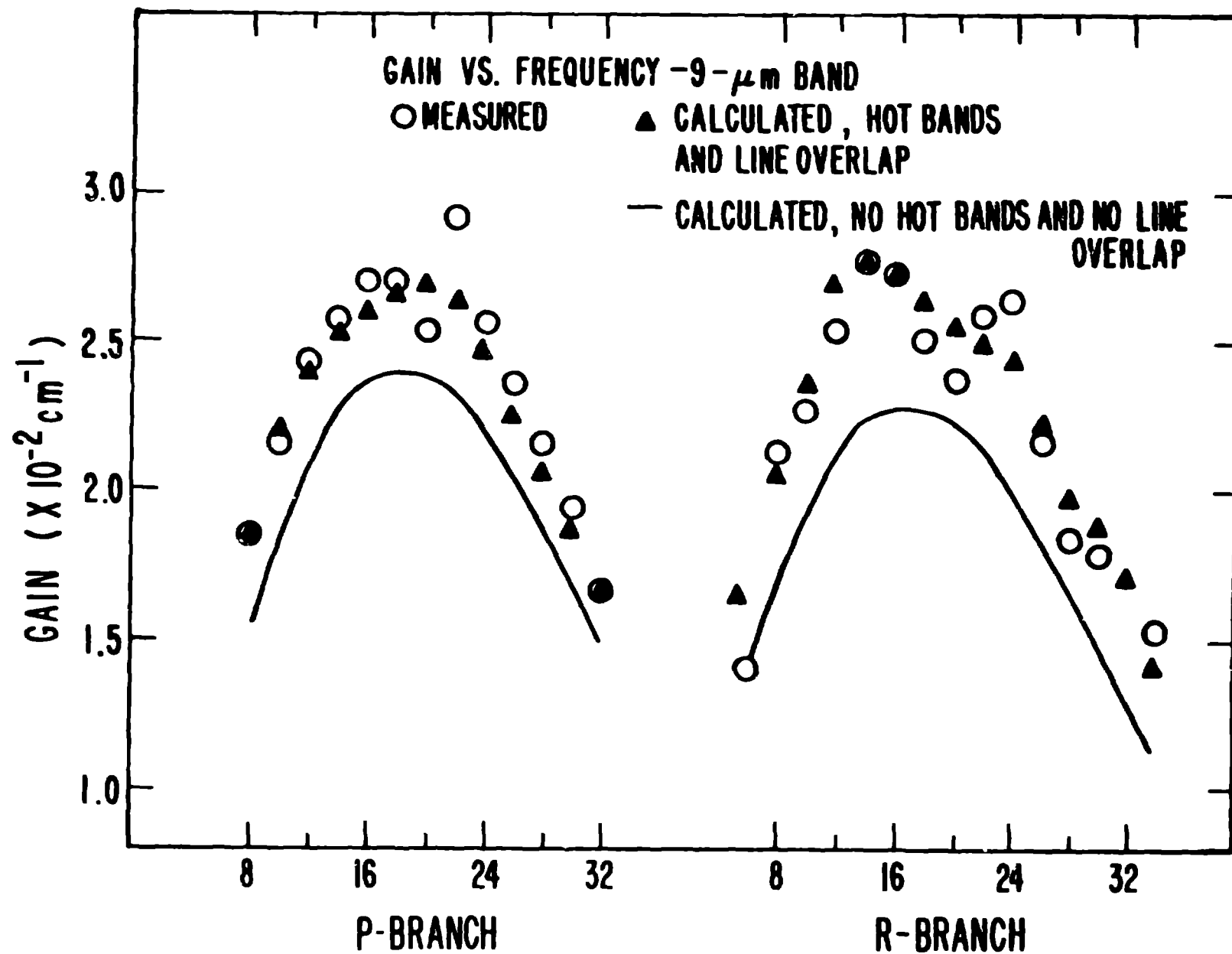
Experimental layout. Probe 1 is set to the reference frequency ($10\text{-}\mu\text{m}$ P(20) or P(22)), while probe 2 is varied in frequency. Both probes are monitored on Optical Engineering spectrum analyzers.

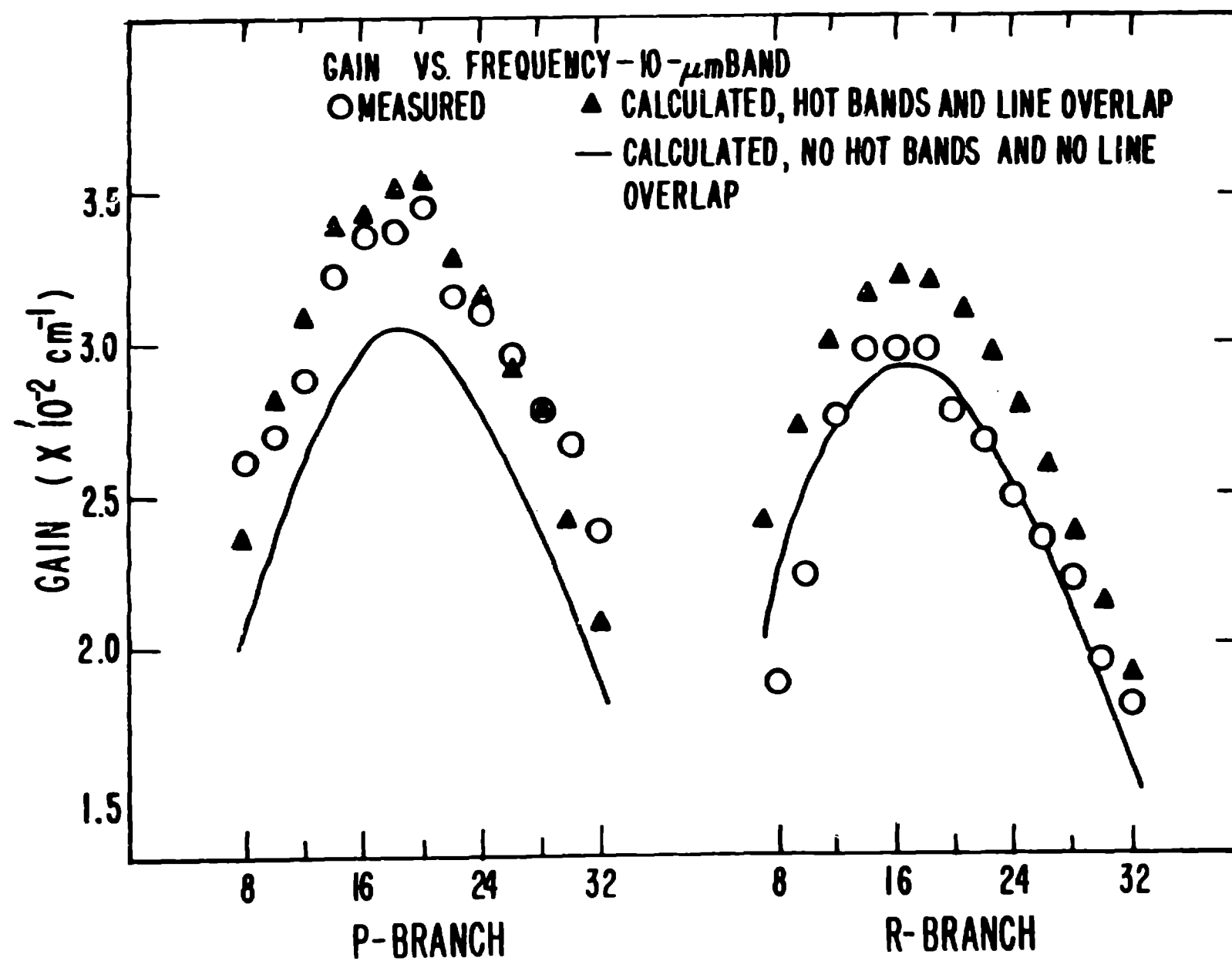


The chopped pulse train from the cw probe laser, before the power amplifier is pumped. The attenuation α ranges from about 3 to 6.5.

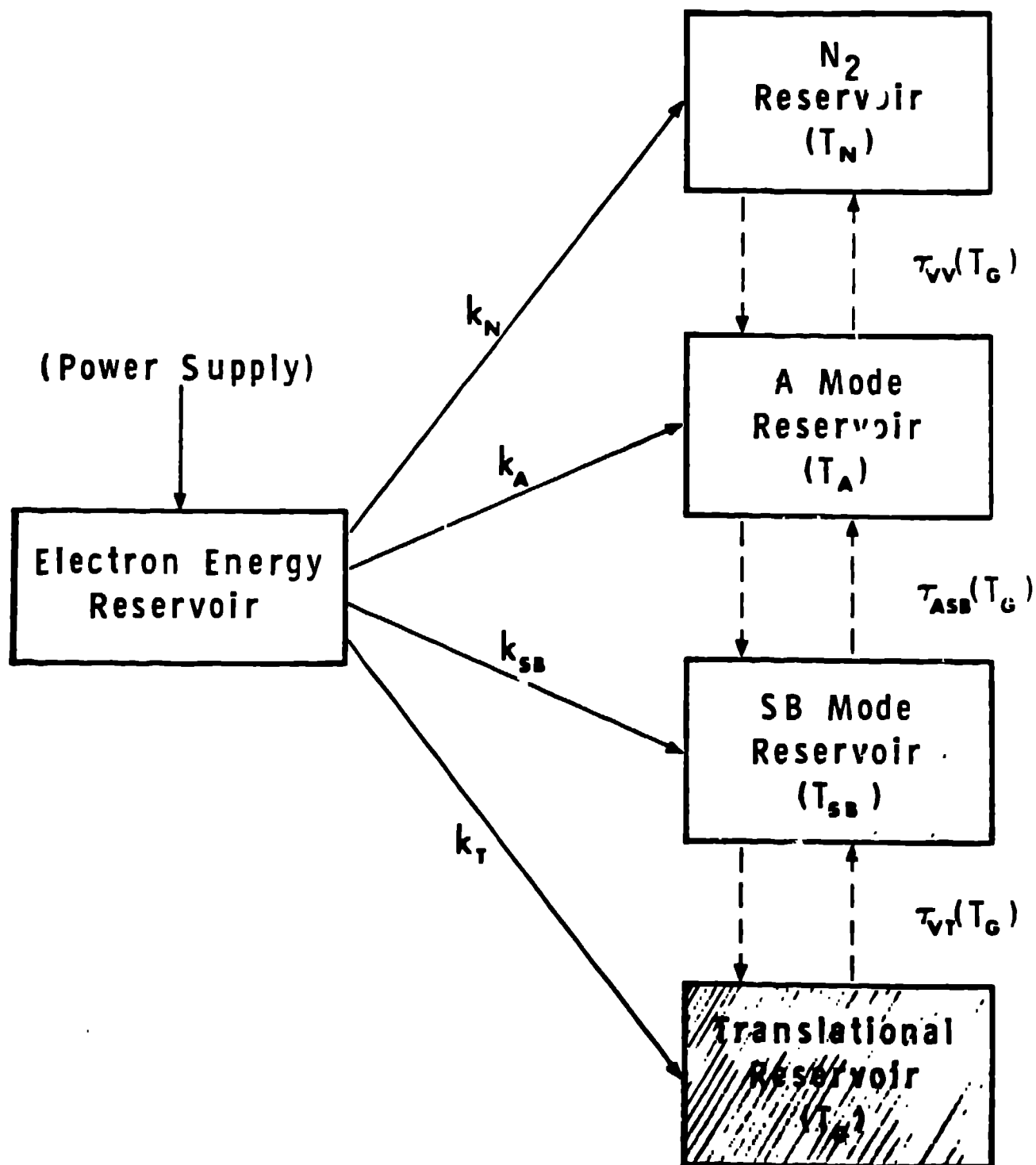


The timing of the pump pulse for the amplifier is arranged so that the attenuated pulse I_1 is amplified by $\exp(g_0 L)$.





Energy Flow Among Thermal Reservoirs In He:N₂:CO₂ Laser Kinetics



Energy Levels and Modes in the He:N₂:CO₂ Kinetics Model

